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Ultraviolet Waveguide Lasers for Phased Array Lidar

C. Paul Christensen
Potomac Photonics, Inc.
4720-E Boston Way
Lanham, MD 20706

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Technical Report

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13. ABSTRACT *(Maximum 200 words)*

This is the final report for a SBIR Phase II investigation of xenon Chloride waveguide laser arrays. Using electrodeless microwave discharge techniques, we have constructed an optimized XeC1 waveguide laser that could serve as the basic building block for a XeC1 laser array with average power in the watt range. The beam produced by the laser is highly multimode. This has been shown to limit the efficiency of the laser, and will hinder its application to coherent arrays.

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atmosphere	1.1013 25 x E +2	kilo pascal (kPa)
degree (angle)	1.745 329 x E -2	radian (rad)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E-7	watt (W)
inch	2.540 000 x E -2	meter (m)
micron	1.000 000 x E-6	meter (m)
pound/in^2 (psi)	6.894 757	kilo pascal (kPa)
torr (mm Hg, 0°C)	1.333 22 x E-1	kilo pascal (kPa)

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SECTION 1
INTRODUCTION

The utility of phased array radar for rapid identification and tracking of multiple targets is well known and has been widely demonstrated. In the microwave portion of the spectrum electronically steered arrays have been developed that exhibit remarkable beam agility and beam forming capabilities. Some of these systems can perform complete hemispherical search with automatic target selection, simultaneously track several targets, illuminate a number of targets with electromagnetic energy, and guide missiles toward them. Phased array optical radars or lidars operating with relatively large synthetic apertures can exhibit many of the same rapid pointing and tracking features associated with microwave systems, and, in addition, are capable of imaging distant targets by scanning with high resolution beams.

1.1. OPTICAL PHASED ARRAY TRANSMITTERS.

The short uv wavelengths associated with excimer lasers also make them interesting candidates for radar applications. Conventional excimer lasers, however, have suffered from design complexity and a lifetime problem as well as somewhat lower efficiency than the infrared sources.

In Phase II we have investigated the feasibility of a novel ultraviolet phased-array radar transmitter based on UV waveguide excimer laser technology. It could offer significant advantages over conventional excimer laser devices in array applications:

(1) Physical dimensions are more suitable for array construction. The waveguide laser configuration simplifies integration of many small-aperture devices.

(2) Microwave-driven electrodeless discharges are used. This allows excimer laser operation with long pulse durations and multikilohertz pulse repetition rates

without rapid gas flow. Simple electronic control of laser pulse duration (50 - 500 ns) is possible.

(3) Higher efficiency may be possible. We have demonstrated laser efficiency exceeding one percent, and recent Soviet work in this area suggests that efficiencies exceeding 5% are achievable[2].

(4) As added benefits the laser discharge section can be constructed from halogen compatible materials, and the microwave source is similar to that used in microwave radars. These latter features greatly extend the potential shelf and operating lifetimes of the system and should facilitate space qualification.

1.2. OVERVIEW OF UV WAVEGUIDE LASER TECHNOLOGY.

Figure 1 schematically shows the waveguide excimer laser configuration and compares it with a more conventional excimer laser. In the microwave discharge waveguide laser a high-pressure gas mixture is contained in the narrow ceramic tube. Excitation energy is provided by a transverse microwave field capacitively coupled through two closely spaced tube walls. The resulting discharge remains spatially homogeneous for long periods and is well suited to laser excitation.

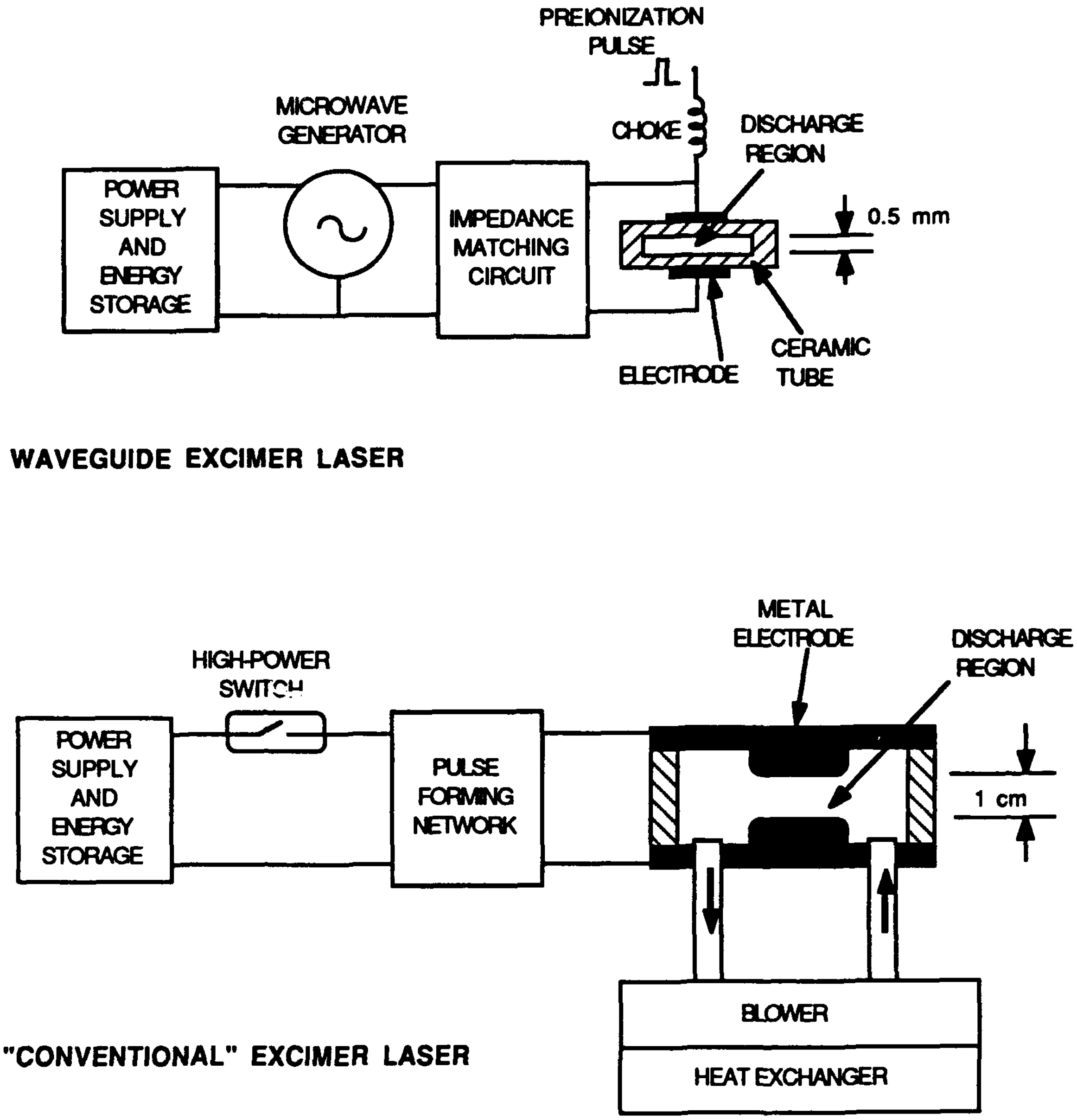


Figure 1. Semi-schematic illustration of waveguide excimer laser configuration (top) and conventional discharge-pumped excimer laser. Note differences in size of the active region, gas flow systems, and electrode location.

1.3. WAVEGUIDE EXCIMER LASERS IN PHASED ARRAYS.

Phased array radars at microwave frequencies utilize many radiators, each with peak power in the 10 - 1000 watt range, distributed over a wide aperture. A similar approach, sketched in Figure 2, has been proposed for the ultraviolet. In the proposed system, a waveguide laser master oscillator operates with good output beam quality and narrow spectral linewidth. The master oscillator beam is divided into beamlets, directed through a phase shifting array and into the final amplifiers. The amplifier sections can be designed for multipass gains in the range of 10 to 100 or operated as injection-locked oscillators with gain as high as 10^5. Beam forming and beam steering is accomplished by adjusting the phase shift imposed on the beamlets by the array of phase shifting elements.

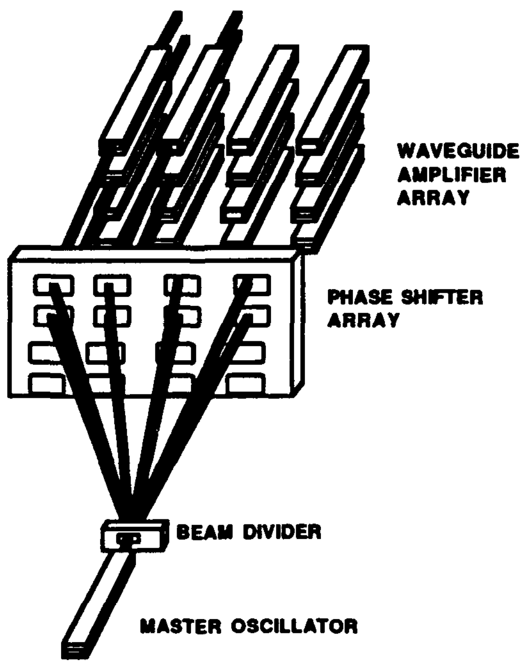


Figure 2. Phased array ultraviolet source fabricated form waveguide excimer lasers. The amplifier sections could be a single pass or multipass amplifiers or injection locked oscillators.

In Phase I we have constructed a narrow band (1 GHz) XeCl waveguide oscillator and investigated its amplification by an XeCl waveguide amplifier. We also demonstrated injection locking of a waveguide excimer laser to a narrowband source. In these studies the injected beam could be delivered directly or through a multimode optical fiber, and no attempt was made to precisely match spatial modes of the master and slave oscillators. Analysis of the slave oscillator output showed that locking could be achieved when the energy injected into the slave unit was as much as five orders of magnitude smaller than the narrow band output energy.

Phase I efforts together with prior work suggested that the essential active elements of a ultraviolet phased array source can be constructed using waveguide excimer laser technology.

SECTION 2
PHASE II OBJECTIVES

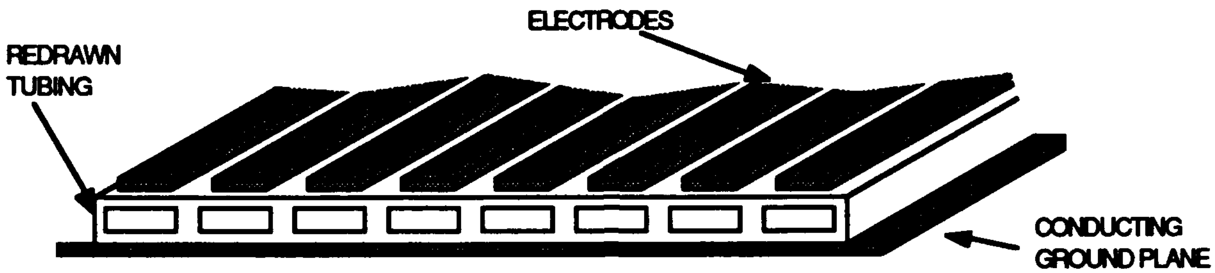
Phase II was intended to be an intermediate step between Phase I feasibility demonstrations and actual construction of large arrays. Phase II work emphasized construction and evaluation of small arrays of ultraviolet waveguide lasers. The following array configurations, based on concepts sketched in Figure 3, were proposed for investigation:

(1) A one dimensional 10 element XeCl waveguide laser array capable of at least one watt of average power. This array demonstrates order-of-magnitude power scaling.

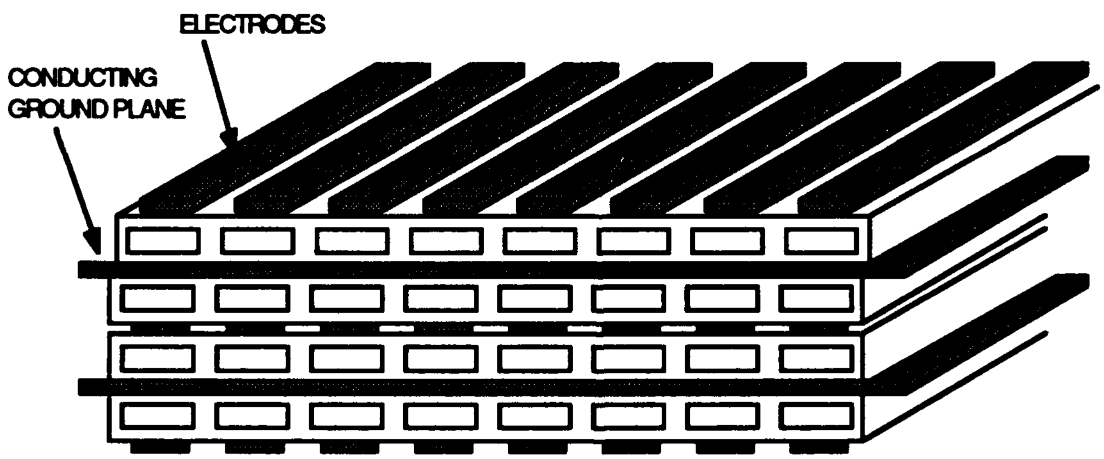
(2) A 2 x 8 two dimensional array. This system demonstrates two dimensional scaling.

(3) A one dimensional 10 element XeCl array in which all of the emission apertures are injection locked to a narrow band oscillator.

(4) A 10 element coherent array in which the phase at each aperture can be separately controlled by electro-optic means. This demonstrates an array with beam scanning capability and electronic control.



One Dimensional Array



Two Dimensional Array

Figure 3. End view of uv waveguide arrays fabricated from redrawn tubing with applied metal electrodes.

SECTION 3
OVERVIEW OF PHASE II ACTIVITY

3.1. WAVEGUIDE EXCIMER TECHNOLOGY AT THE BEGINNING OF THE PROJECT.

At the start of Phase II, waveguide excimer lasers manufactured by Potomac Photonics utilized 3 GHz magnetrons excited by a large high-voltage pulse generator. Microwave power was delivered to the discharge structure through hollow waveguide sections. The discharge tube itself was immersed in a fluorocarbon fluid to avoid arcing on the outside of the tube due to high microwave fields produced during operation. The size of the microwave generation and delivery components did not allow use of several generators to produce the necessary power to excite a discharge array. Use of a fluid dielectric is not compatible with array fabrication, since an array typically has many cracks and crevices where bubbles form and allow arcing and damage. A fluid dielectric also is not appropriate in a mobile system that will be operated in many orientations.

As a consequence of these limitations, substantial engineering development was required to bring the state of the art to the point that array fabrication was possible. Emphasis was upon development of a single array element with features that would allow it to serve as a building block for construction of the proposed arrays.

3.2. CONSTRUCTION OF THE BASIC ARRAY ELEMENT.

The original project plan allocated the first months of the project to development of a discharge structure and microwave excitation system with the following features:

(a) Discharge tube with optimum geometry for high efficiency with good transverse mode quality. Tube encapsulated by solid dielectric.

(b) Development of fixtures allowing mounting of the discharge tube so that deviations from straightness along its entire length were less than 2% of the tube bore.

(c) Microwave generator configuration of reduced size and configured to be compatible with array fabrication.

(d) Delivery of more than 90% of the microwave power to the discharge plasma.

3.3. FABRICATION OF THE DISCHARGE STRUCTURE.

To minimize optical waveguiding losses and mode conversion the discharge tube must be mounted so that it is as straight as possible. Before mounting techniques can be perfected, however, techniques for measuring straightness must be developed. Several approaches to measurement of straightness were investigated. A mechanical stylus attached to a digital micrometer was used with limited success to measure the height of the tube relative to a granite surface plate. Radial curvature of the tube wall, however, complicated the measurement. Optical probe concepts similar to confocal microscopy were explored, but were found to exhibit poor repeatability. Finally, a video imaging approach that measured variations in tube position in two dimensions relative to reference surfaces was found to give acceptable performance with resolution of +/- .001" for a tube with a .020" bore.

Once a measurement system was perfected, work could begin on construction of the discharge tube mount, sketched in cross-section in Figure 4.

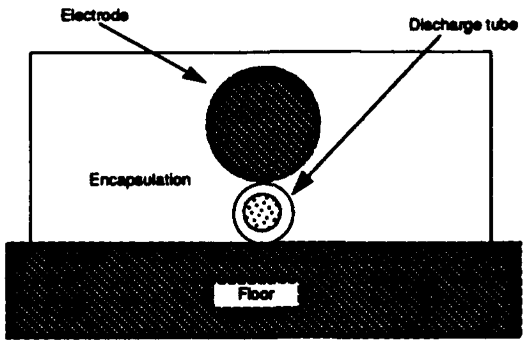


Figure 4. Cross-section of the discharge tube mount.

Discharge tubes are fabricated from redrawn glass or fused silica and do not have great rigidity. During assembly of the structure, they tend to be pressed or drawn toward the floor of the assembly, so that the floor must be flat over its length if the tube is to remain straight. Using the optical measurement system, we experimented with several floor geometries to find a configuration that could machined flat to +/- 25 µm over a length of 40 cm. A heated jig was also constructed to allow uniform heating of the mount to avoid thermal distortion during curing of the encapsulation material.

Materials suitable for encapsulation of the discharge tube and electrode were also investigated. The material should exhibit high dielectric strength, low microwave loss, and good thermal conductivity. Several thermoset epoxies exhibit acceptable loss at low frequencies and good thermal conductivity, but little was known about microwave losses and dielectric strength. Experimentation with several materials finally resulted in identification of a thermally conductive epoxy with acceptable dielectric properties. Techniques for degassing the epoxy to enhance dielectric strength were explored. Mounting jigs and fixtures for positioning of the electrode structure were constructed, and an optical technique for aligning the electrode relative to the tube was developed.

3.4. MICROWAVE GENERATION AND DELIVERY.

At the beginning of Phase II, the magnetron power supply and pulse generator accounted for about one third of the size and cost of current waveguide excimer lasers. The pulse generator used large and expensive vacuum switch tubes and requires a 12 kV cw power supply for operation. As a part of the contract work we have extended earlier work on a magnetron pulse generator that utilizes newly developed MOSFET transistors for power conditioning and operates from a 500 V power supply. We have constructed and tested a compact and inexpensive MOSFET pulse generator that can produce submicrosecond pulses of up to 10 kV amplitude, 150 kW peak power, and 200 watts of average power. This switch can be adapted to excitation of almost any magnetron of interest. The new generator is much smaller than the switch tube alone and eliminates the need for vacuum tube bias circuits. Operation from a 500 V source also allows reduction of the size and cost of the power supply by approximately a factor of 5.

In Phase II we also have utilized a more compact magnetron for generation of the microwave excitation and developed a simpler power delivery system that eliminates the need for bulky hollow waveguides. The entire system is now constructed using microstrip waveguides. As a result of the smaller geometries involved with the microstrip approach, electric fields throughout the power delivery system are higher than those in the original circuit, and we have been forced to develop insulating structures that can suppress formation of spurious arcs. Substantial work in this area has resulted in a power delivery system that utilizes solid dielectric throughout, is quite compact, and can operate for long periods at pulse power levels of 50 - 100 kilowatts. Development of the new power delivery and discharge structure represents a significant advance in waveguide excimer laser technology.

3.5. EFFICIENCY AND SPECIFIC POWER OF WAVEGUIDE XECL LASERS.

Waveguide laser arrays for space applications must exhibit relatively high average power and efficiency. Electrical/optical conversion efficiency greater than 1% has been measured for a XeCl laser utilizing a 0.5 mm x 5 mm x 40 cm discharge[1]. Conventional, discharge-pumped XeCl lasers often exhibit electrical/optical efficiencies in the range of 2 to 4%[2], and a microwave-pumped, nonwaveguiding XeCl laser with 5% efficiency has been described by Soviet investigators[3]. Efficiencies of less than 1% probably are not acceptable for space based applications. It is important, therefore, to understand in as much detail as possible any factors that influence efficiency in waveguide XeCl devices.

Long and Bhaumik [4] have shown that the output intensity, I, of an excimer laser of length, L, with output coupling reflectivity, R, is determined by its small signal gain, g_0, the nonsaturable loss, a, and the saturation intensity of the excimer medium, I_s:

$$I = \frac{I_s}{2}\left(\frac{g_0}{a + \frac{1}{2L}\ln\frac{1}{R}} - 1\right)$$

Since I_s is a determined by the lifetime of the upper laser state and the stimulated emission cross-section, it is a constant of the medium. For XeCl lasers the saturation intensity has been estimated to be about 250 kW/cm^2 [2] and is expected to be relatively independent of pressure.

The loss, a, includes the effects of optical absorption by various molecules and ions in the laser gas as well as spurious reflections at windows, waveguiding losses, and similar losses. In large XeCl lasers the dominant intracavity loss is due to absorption by plasma species such as chlorine ions, excited rare gas species and Xe_2Cl^* trimers [3][4]. We would expect similar absorption to occur in waveguide lasers. Waveguide lasers, however, could be expected to have additional losses due to waveguiding and mirror-waveguide coupling (inefficient coupling of the laser beam reflected from the mirror into the waveguide) that do not occur in large aperture XeCl lasers. In optimally designed and constructed waveguide lasers the guiding loss of the hollow tube can be estimated from well known formulas to be less than 0.1% per cm for a 0.5 mm dia. waveguide, and mirror coupling losses are expected to be less than 1 % per pass. These losses should therefore be much smaller than the estimated .25 - .5 %/cm loss associated with the plasma[5].

The gain, g_0 , in conventional discharge-pumped XeCl lasers has been found to be linearly proportional to the pump power over a wide range [2] and is approximately given by:

$$g_0 \approx (6\%/\text{cm})[P/(1000\text{kW/cm}^3)]$$

where P is the pump power per unit volume. Gain in a waveguide excimer laser with an active volume of 0.05 x 0.2 x 35 = 0.35 cm^3 pumped by two 50 kW magnetrons has been measured to be approximately 4%/cm in the Phase I experiments. If all of the microwave power is delivered to the discharge, the pump power density is approximately 285 kW/cm^3. This level of excitation would produce a gain of only 1.7%/cm in a larger system. Consequently, these preliminary measurements are consistent with the Soviet results and suggest that the laser species is produced more efficiently in a microwave discharge. Waveguide excimer lasers, therefore, should exhibit efficiency and specific power comparable to larger excimer systems, provided that intracavity losses can be minimized.

3.6. OPTIMIZATION OF DISCHARGE TUBE GEOMETRY.

For the available 50 kW pump power, we should expect that there will exist an optimum discharge tube shape and volume that will produce highest conversion efficiency and best beam quality. Qualitatively, smaller bore tubes should exhibit higher waveguiding losses for a given beam divergence and thus tend to generate better beam quality. However, overall cavity losses associated with waveguiding and mirror coupling may also be higher, so that optical extraction efficiency is lower. The discharge volume must be such that the available microwave power generates high gain, but does not overpump the plasma to the point that the efficiency of production of the laser species is reduced.

Several tube geometries were investigated to identify the configuration that best converted the microwave output from a single magnetron to 308 nm laser emission. Round tubes of 0.2 mm and 0.5 mm bore, and rectangular tubes of 0.2 x 2 mm, 0.5 x 1 mm, and 0.5 x 2 mm bore were investigated. In general, the rectangular tubes were found to provide best efficiency. Beam divergence was found to be a function of the smallest tube dimension, with, for example 0.5 x 2 mm and 0.5 mm round tubes exhibiting similar beam divergence. Figures 6, 7, and 8 show typical dependence of laser output on magnetron current for three rectangular tube geometries. Since the microwave pump power is linearly proportional to the magnetron current, overpumping of the laser medium will be reflected as a plateau in the laser output at high current levels.

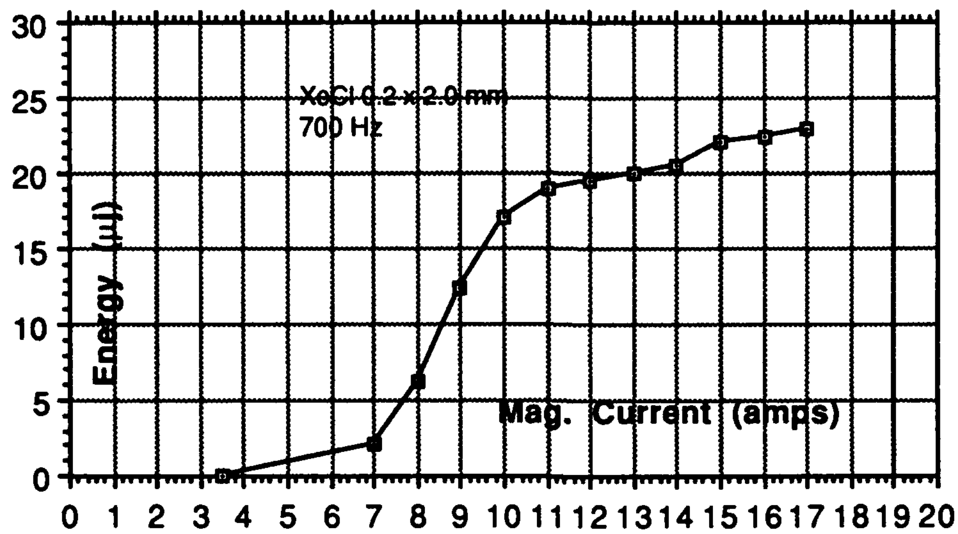


Figure 5. Pulse energy as a function of magnetron current for a 0.2 mm x 2 mm x 20 cm discharge tube.

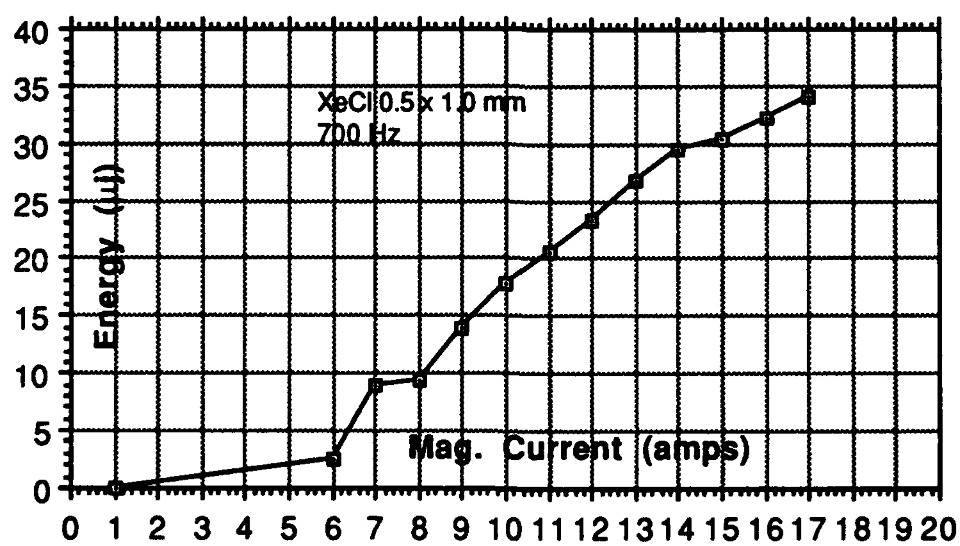


Figure 6. Pulse energy as a function of peak magnetron current for a 0.5 mm x 1 mm x 20 cm discharge tube.

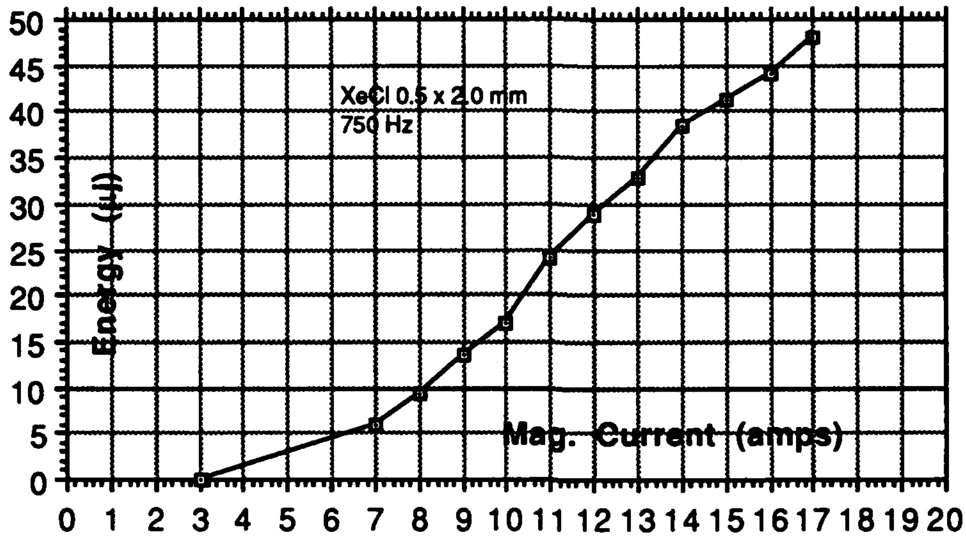


Figure 7. Pulse energy as a function of peak magnetron current for a 0.5 mm x 2 mm x 20 cm discharge tube.

The curves above show saturation of the output of the 0.2 mm x 2 mm tubes at pump levels corresponding to approximately one half of the available magnetron power. Although the excited volume of the 0.5 x 1 mm tube is only slightly larger, the pump saturation effect is much less pronounced. This suggests that other pump-related processes such as thermally-induced optical distortion may also play an important role in determining laser efficiency. The 0.5 mm x 5 mm tube consistently exhibited higher power and efficiency than the smaller bore units. This may be a result of somewhat smaller waveguiding and mirror coupling losses with the larger bore tube.

3.7. OPTICAL FILLING FACTOR AND TRANSVERSE MODE.

Beam profiles of the various discharge tubes were measured at several distances from the the tube end to determine the optical filling factor of the tube and the transverse mode profile. It was found that the most information regarding cavity modes and filling factor was obtained by observing the beam profile at the tube exit using the imaging arrangement shown in Figure 8. The tube end was imaged on a CCD camera, with the camera output directed to a frame grabber on a Macintosh computer. The digitized images could then be enhanced, analyzed, and stored

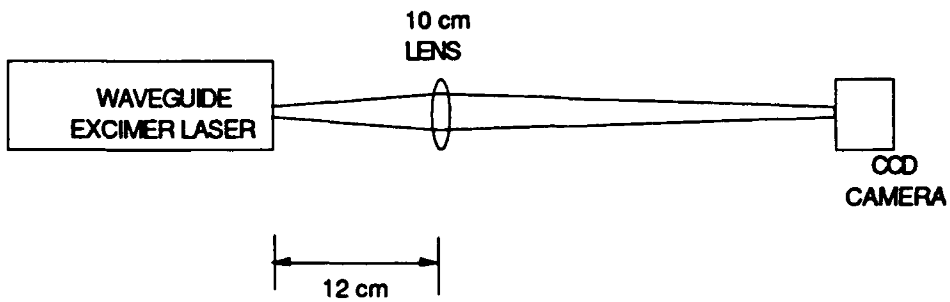


Figure 8. Optical arrangement used for analysis of the laser beam profile.

Beam profiles for three discharge tube geometries are shown in Figures 11, 12 and 13 of th Appendix. For all of these tubes we typically observed a series of regular striations in the beam normal to the small dimension of the tube. This is the direction in which the waveguiding effect is strongest. In the large dimension, the beam filling factor appeared to be largest for the larger bore tubes.

For many lasers, the transverse mode structure of the beam is strongly affected by the curvature of the cavity mirrors. We have investigated the beam profile for the three tubes using the following sets of cavity mirrors separated by 22 cm: flat/flat, flat/curved(30 cm), curved(30 cm)/curved(30 cm). Differences in beam profile between the flat and curved mirror cavities were found to be small, suggesting that the waveguide itself, together with any optical inhomogeniety in the active medium, have the strongest influence on the transverse beam profile.

3.8. PERFORMANCE OF THE OPTIMIZED SINGLE TUBE LASER.

Using all of the information gleaned from the above experiments, we constructed an optimized single tube laser that could serve as a building block for a high power array. The laser emission is highly multimode, and the beam divergence is approximately 9 times diffraction limit. Although the beam quality of this device may not be suitable for use in a coherent array, it has significant potential for power scalability. A ten-element array based on this single element building block should be capable of meeting the Phase II goal of one watt of average power.

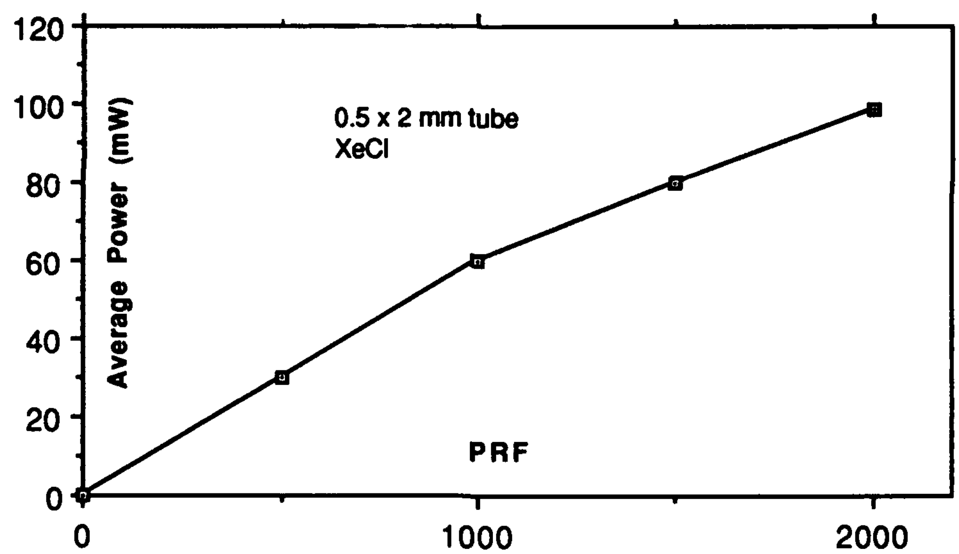


Figure 9. Average power as a function of pulse repetition frequency for an optimized single element module.

3.9. INFLUENCE OF WAVEGUIDING LOSS AND TRANSVERSE MODE ON EFFICIENCY.

Efficiencies of approximately 0.4% have been measured for the optimzed single tube lasers like that of Figure 9. Therefore, the efficiencies observed for the waveguide lasers under investigation are as much as an order of magnitude lower than other excimer systems. It is important to understand the possible reasons for the reduced efficiency.

Section 3.9 above suggests that the problem lies with optical cavity losses, and equations in that section can be used to estimate the effect of losses in a XeCl laser of known gain. Figure 10 shows calculated laser output energy as a function of waveguide and mirror coupling losses for a 0.5 mm x 2 mm discharge tube 35 mm in length characterized by a gain of 4% per cm. Note that output energy is strongly influenced by cavity losses.

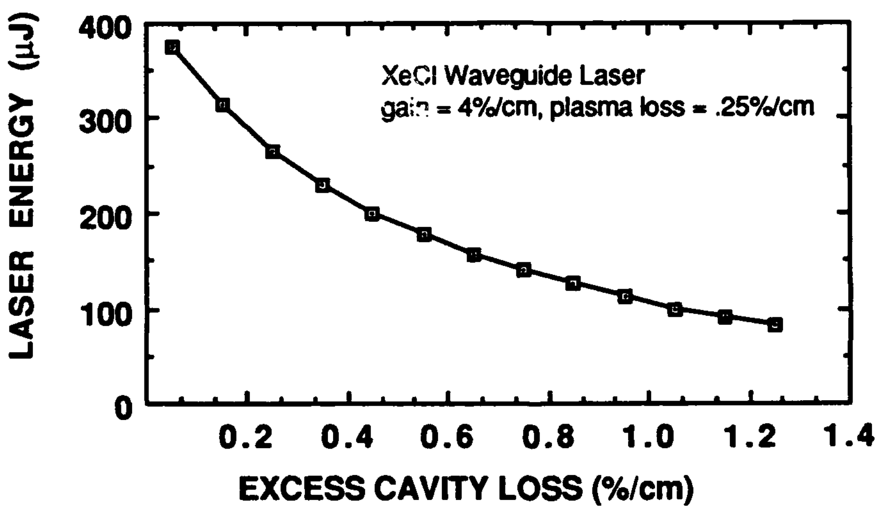


Fig. 10. Effect of excess loss (waveguiding loss, mirror coupling loss, etc.) on a 0.05 x 0.2 x 35 cm waveguide excimer laser with gain of 4%/cm and absorption loss by plasma of .25%/cm. Reflectivity of output coupler is 80%.

Cavity losses of a few tenths of a per cent per centimeter are adequate to reduce the laser output by factors of 2 - 3. For the 0.5 mm x 2 mm x 35 cm tube modeled above waveguiding and mirror coupling losses that average only 0.8%/cm are are consistent with the laser performance but are adequate to reduce the output by a factor of 3. Similar calculations have been carried out for a variety of other tube geometries. Excess losses of the order of 1.0 - 1.2%/cm have been found to be consistent with the measured laser efficiency of the discharge tubes used in the beam quality studies.

Waveguide excimer laser emission typically exhibits both low and high divergence components. We have developed a simple analysis based on geometric optics for estimating waveguiding and mirror coupling losses as a function of beam divergence in hollow waveguides. The analysis shows that although 30 - 50% of the laser output is in a low divergence mode the higher divergence components can exhibit very high losses. We find that total average losses of 1 - 2%/cm are consistent with the average divergence of the laser output. These losses are about equally distributed between mirror - waveguide coupling losses and waveguide transmission losses.

The above discussion suggests that waveguide excimers are capable of efficient operation but that excessive beam divergence can dramatically reduce laser output energy and efficiency. An important source of high beam divergence is curvature, bumps, and surface roughness in the waveguide bore that scatter light from low order modes into higher-order components. However, the laser gas is excited at very high power levels during operation, and can heat to several hundred degrees centigrade in less than one microsecond. Nonuniform heating can lead to thermally-induced optical distortions, or gas lens effects, that also can act to excite high divergence modes. The small size of the waveguide bore makes quantitative measurement of these effects difficult, but it seems likely that both influence laser performance.

3.10. **A TWO ELEMENT ARRAY.**

As part of the Phase II effort, we constructed a two element array. The array was constructed from two 0.5 mm dia. x 20 cm discharge tubes excited by a single magnetron. A profile of the nearfield array emission is shown in Fig. 14 of the Appendix. An energy of 17 µJ was obtained from the array at a pulse repetition rate of 500 Hz. Although the efficiency and energy obtained from the simple array was not impressive, to our knowledge it is the only excimer laser array that has been reported.

3.11. APPLICATION TO COMMERCIAL PRODUCTS.

Much of the microwave generation and discharge technology described above is currently being transferred to commercial lasers manufactured by Potomac Photonics. These technical improvements will lead to commercial availablilty of waveguide excimer lasers that are about one-half the size of earlier units while at the same time generating higher output power. As an added benefit the new lasers can be constructed at lower cost. Although these systems emit a highly multimode beam, their output is suitable for a large number of applications. We believe that availablity of these improved uv sources in the commercial marketplace will stimulate development of new applications and could be an enabling technology for several microfabrication and chemical analysis systems.

Manufacturing prototypes of one and two magnetron lasers have been constructed and are undergoing final test. The laser is capable of producing more than 150 mW of average power at both 308 and 248 nm with pulse repetition rates extending to 2 kHz.

SECTION 4
CONCLUSIONS

Issues associated with fabrication of coherent, high-power uv laser arrays using waveguide excimer laser technology have been investigated extensively. A single element building block that could serve as the basis for a 10 element, one-watt array has been constructed. However, the presence of high divergence transverse modes in the laser cavity results in emission that is not suitable for use in coherent arrays and also leads to high intracavity waveguiding and mirror coupling losses that reduce laser power and efficiency. The high divergence modes are believed to to due to waveguide imperfections and gas lens effects. They have been persistently evident in all devices constructed to date.

In spite of problems in production of diffraction-limited emission, the technology developed in Phase II has potential utility in several industrial applications.

SECTION 5

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APPENDIX

LASER BEAM PROFILES

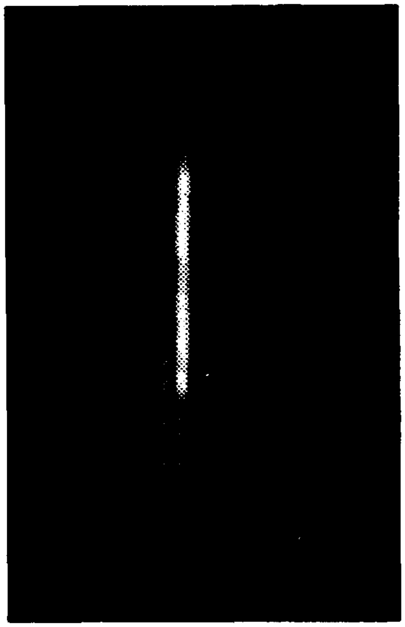

Figure 11. CCD camera photograph of beam profile at tube end of 0.2 mm x 2 mm rectangular tube.

Figure 12. Beam profile at tube end for 0.5 mm x 1 mm tube.

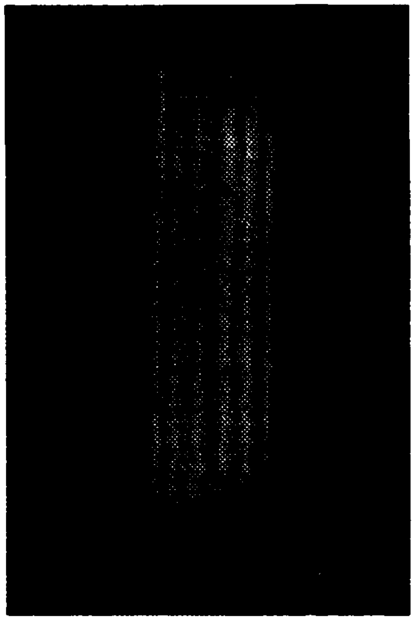

Figure 13. Beam profile at tube end for 0.5 mm x 2 mm tube.

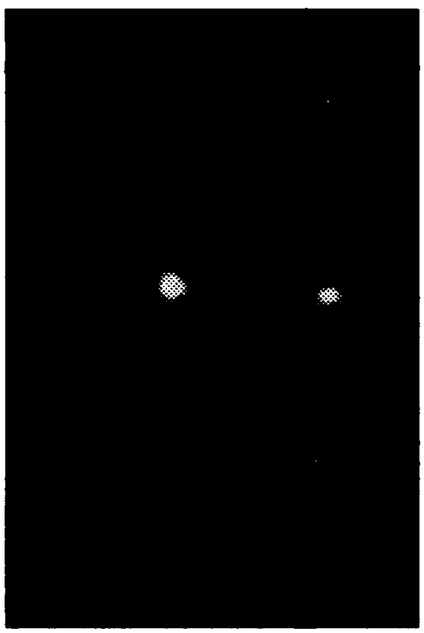

Figure 14. Emission pattern at array exit of 2 element array constructed from 0.5 mm dia. tubes.

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